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Adiabatic compression of compact tori

(Current DOE Phase II and Phase I SBIR)

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Outline

--Woodruff Scientific - who we are and what we do.

--Current Phase II project overview: experiment and simulation.

--Current Phase I SBIR project overview: simulation results and analytic modeling for point design of a compression experiment.

--Summary

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Our team: highly experienced staff (decades of plasma physics expertise)

Dr. Simon Woodruff – President and PI of current grants, Affiliate Associate Prof, UW

Dr. Angus Macnab – Principal Research Scientist (Computational physicist).

Dr. Tim Ziemba – Principal Research Scientist (Experimental physicist).

Dr. Kenneth Miller – Principal Research Scientist (Experimental physicist).

+ consultants and advocates ->

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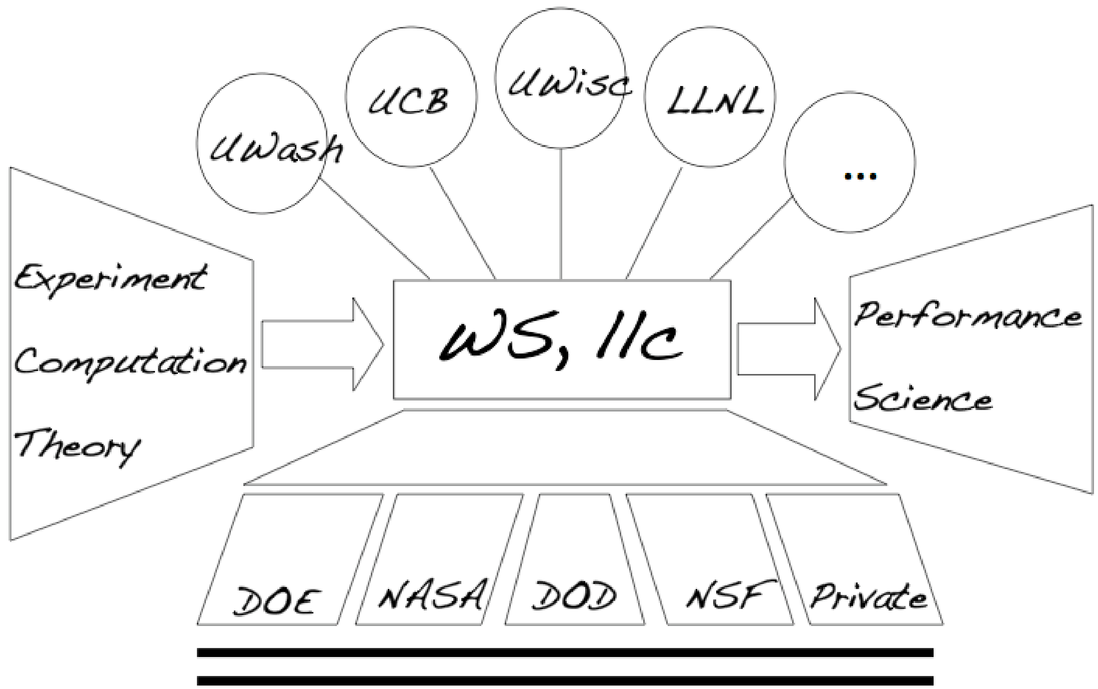
Business model: obtain broad support base to help push innovative fusion concepts along.

We aim to address critical scientific issues on the path to economic fusion energy by building experiments, running advanced simulations and by careful analytical modeling.

We aim to deliver both value science and advance the performance of innovative fusion concepts.



We will continue collaborations with universities, national labs and industry.

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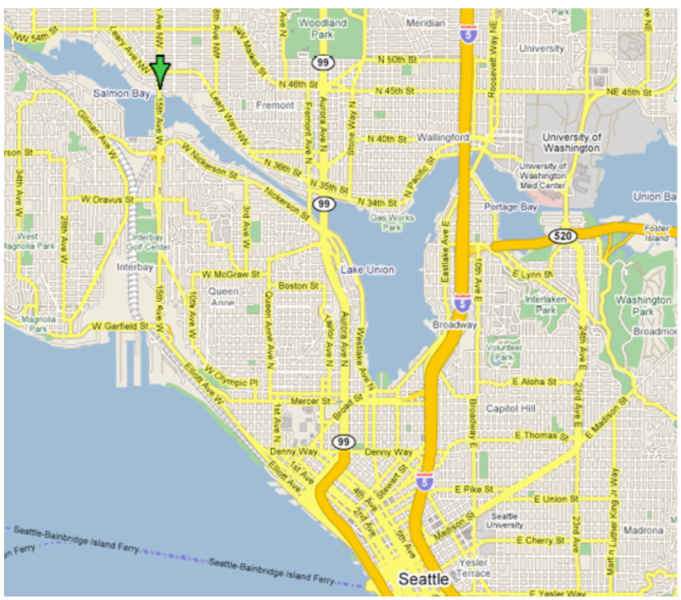
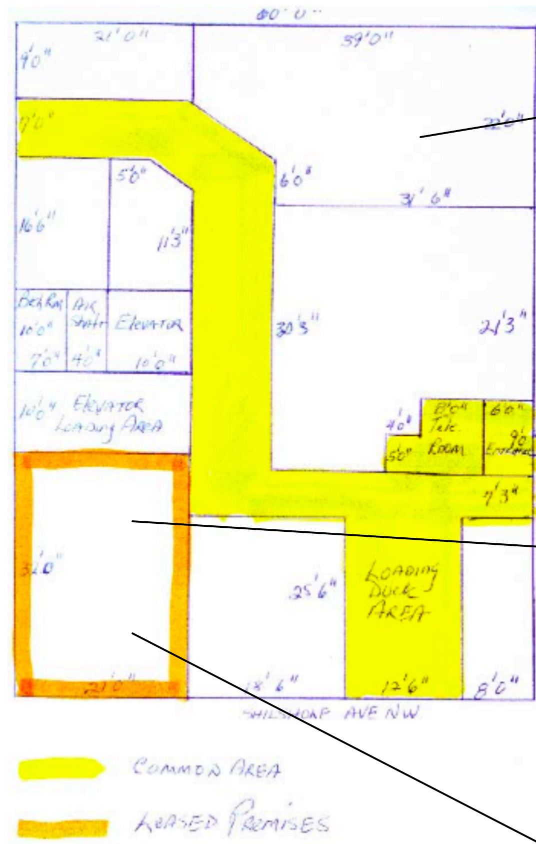
Facilities





Lab and offices are located in Ballard (10 minutes from UW by bicycle).

Computing: lots of NERSC time (Bassi).

What is SBIR?

Small **B**usiness **I**nnovation **R**esearch grants

--Phase I: 9 months ~100k

--Phase II: up to 2 years, ~350k/year

--Phase III: commercialization phase -

VC/angel/industrial partnering for commercialization

Continue development with other gov funding

Sell full system or sub-systems.

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Our current Phase II project funded by DOE SBIR:

Field build-up by multi-pulsed formation and compression of spheromak plasmas

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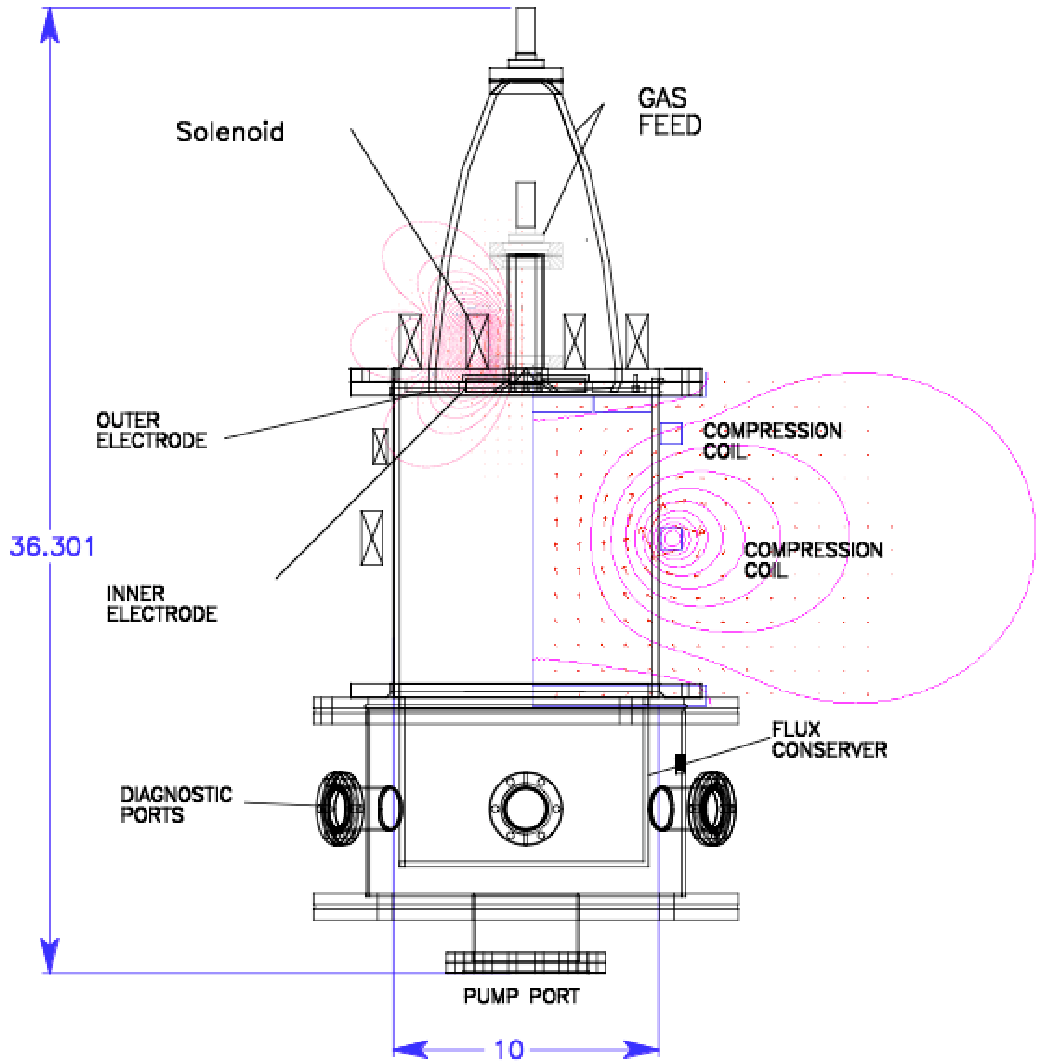
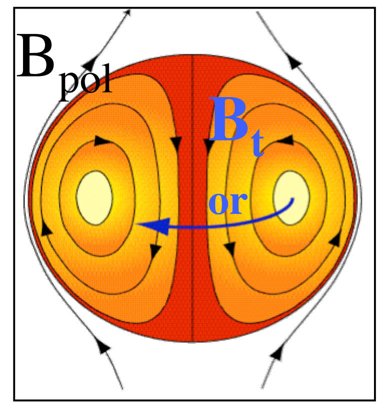
DOE Phase II SBIR: compression of multiple CTs to generate strong magnetic fields.



Spheromak formation with planar gun (per Bellan).



Compression coils to push plasma downstream into flux conserver.

In so doing, we will explore: interaction of fast (M>1) plasmas, shocks, mixing, pressure limits, R-T instability, and reconnection.

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Experimental parameters.

Parameter	
Major Radius (cm)	12
Minor Radius (cm)	6
Plasma Current (kA)	100
Magnetic field B_0(T)	0.1
Gun flux (mWb)	<7
Current rise time (μs)	10
Plasma velocity (km/s)	~100
Pulse Length, (ms)	<1
Density, n ($10^{19}m^{-3}$)	2-10
Electron Temperature, T_e (eV)	<50
Ion Temperature, T_i (eV)	<100
Beta, $=2\mu_0\langle p\rangle/B(a)^2$	0.05

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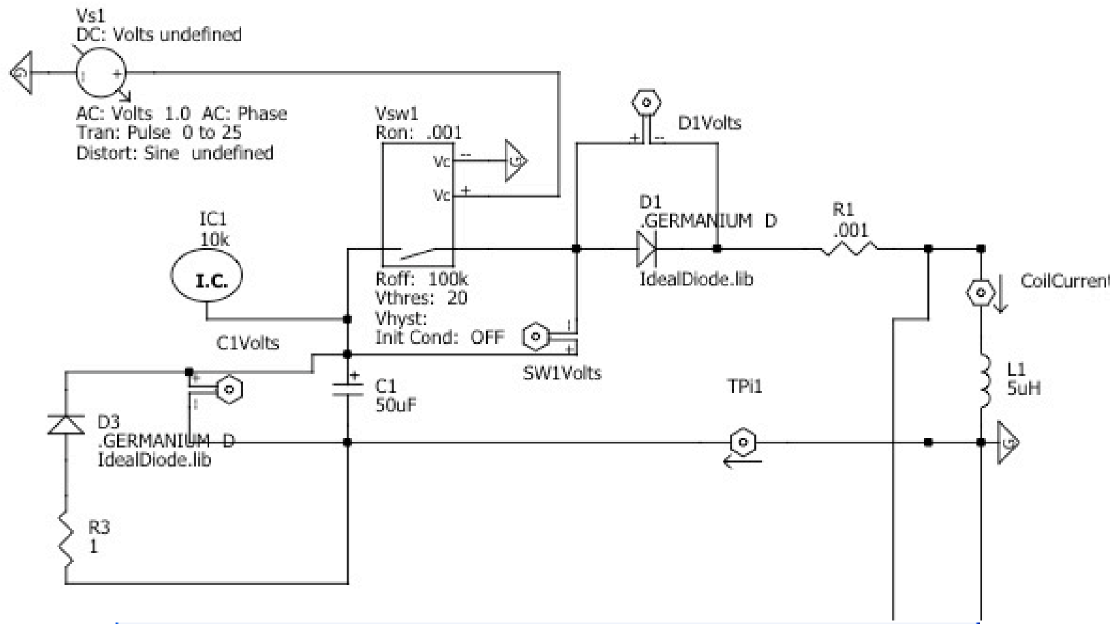
9 nearly identical bank modules will energize the gun and coils.

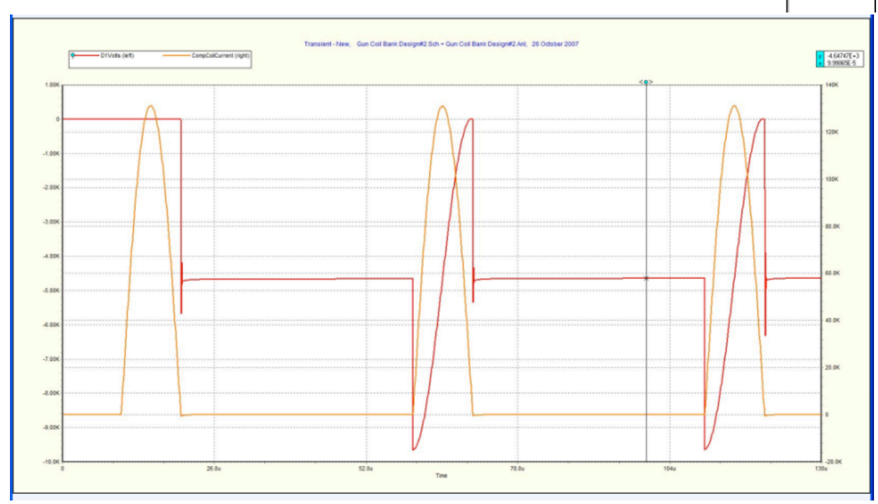
9 x 10kV 50μF bank modules will deliver a train of 3 100kA pulses (~30μs apart) to the gun and two coils.

We aim to rectify the current pulses (pushes diode performance (in terms of dI/dt))

A slow bank will drive the solenoid.

(Modeling with 5Spice)





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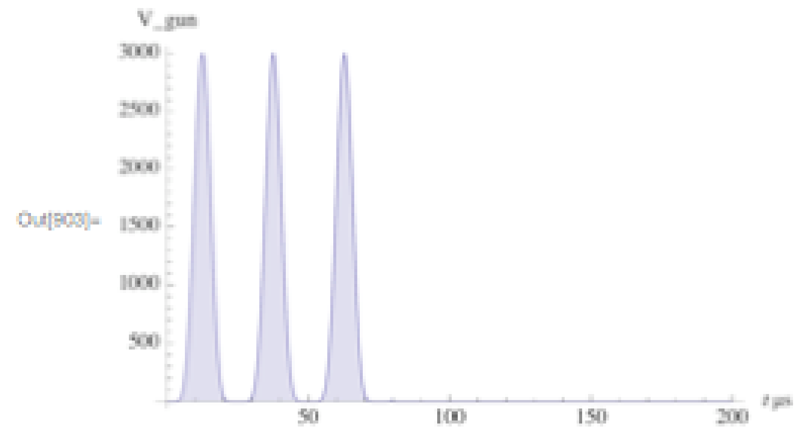
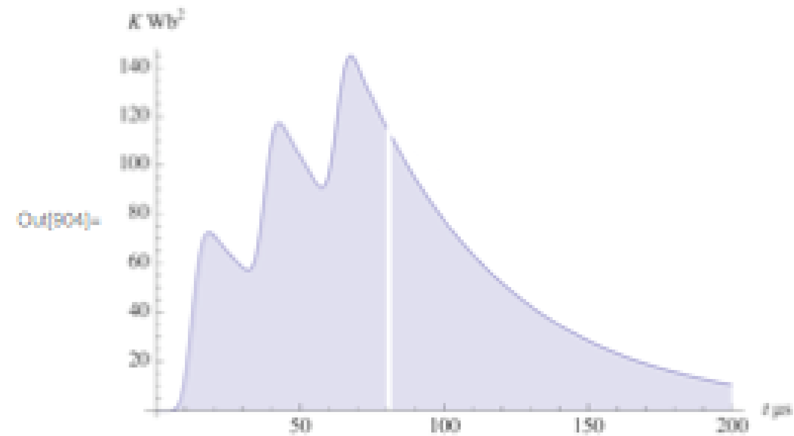
Objectives for multiple-pulsed system: flux amplification by overcoming pressure limits.

Macroscopic helicity injection:

$$\frac{\partial K}{\partial t} = \frac{-K}{\tau_K} + 2V_{gun}\psi_{gun}$$

$$K(t) = \exp\left(\int_0^t \frac{-dt}{\tau_K}\right)\int_0^t 2V_{gun}(t')\psi_{gun}(t')\exp\left(\int_0^{t'} \frac{dt''}{\tau_K}\right)$$





--Examine pressure limits at the entrance to flux conserver.

--Examine forced reconnection between spheromaks.

--Obviate dissipation limits by ensuring surface conditioning.

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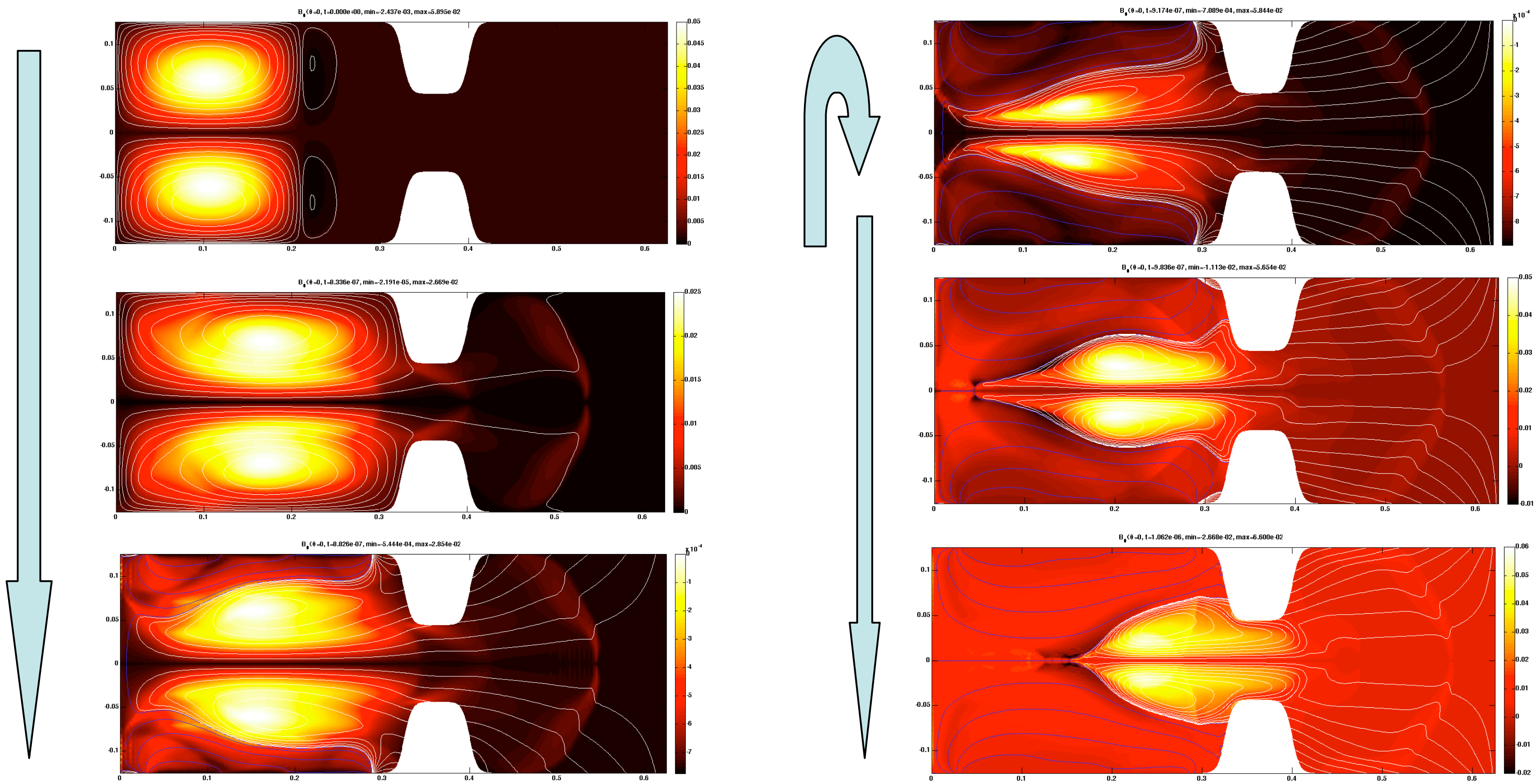
Initial NIMROD simulations of the formation and compression of a spheromak.

Spheromaks initialized from BFM, allowed to evolve a few time-steps.

Coil compression forces Spheromak into aperture.



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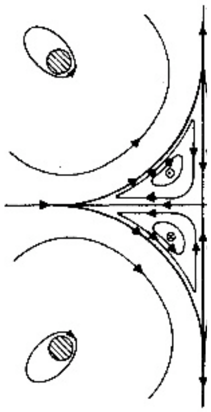
Stability of the configuration to tiliting is being examined computationally/analytically



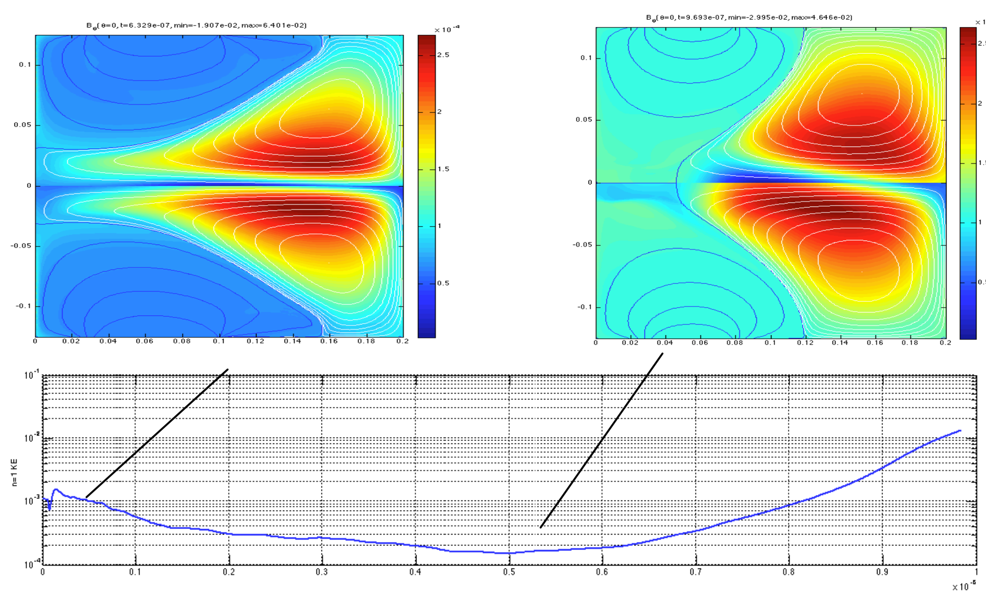
Analytic (linear) stability analysis of Rosenburg and Bussac being revisted for our case.

Linear analysis also considered by Shumlak - found that R/a must remain <1.6

Dynamic compressed + elongated spheromaks are given a small initial perturbation.

Growth of the tilt (n=1) instability is monitored.

Leading into experimental design for tilt-suppression (inner conductor).



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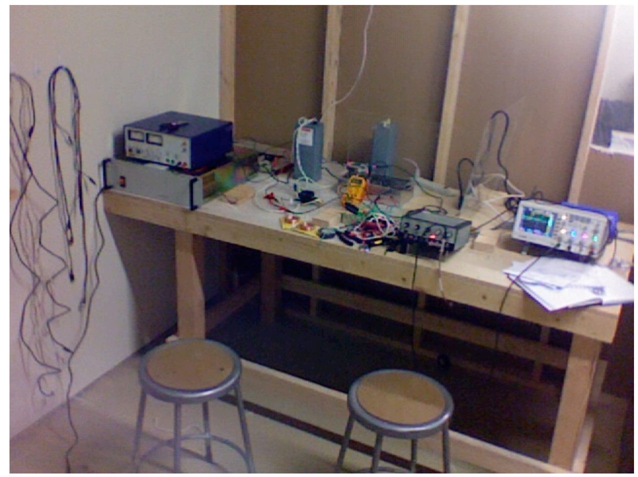
Progress in first 4 months.

Phase II project under construction - progress in first 4 months:

1. Hired staff.
2. Found lab, built out lab - safely.
3. CDRs and EDRs for all subsystems done
4. Initial simulations, considering stability.
5. Ending procurement in January - construction done by March/April.



Diodes and spark gap switches undergoing HV testing

DAQ rack being populated with NI equipment.

Diagnostics - mostly B-dot, then rogs, HV probes.

Pump deck and expt support structure built.

Pumps + gauges arriving this week.

Our current Phase I project funded by DOE SBIR:

Adiabatic compression of a magnetized plasma

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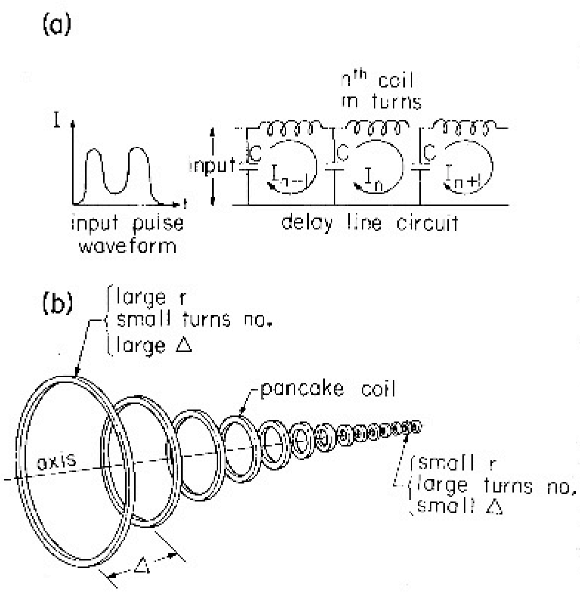
Phase I SBIR: Consider various compression schemes to adiabatically compress CT

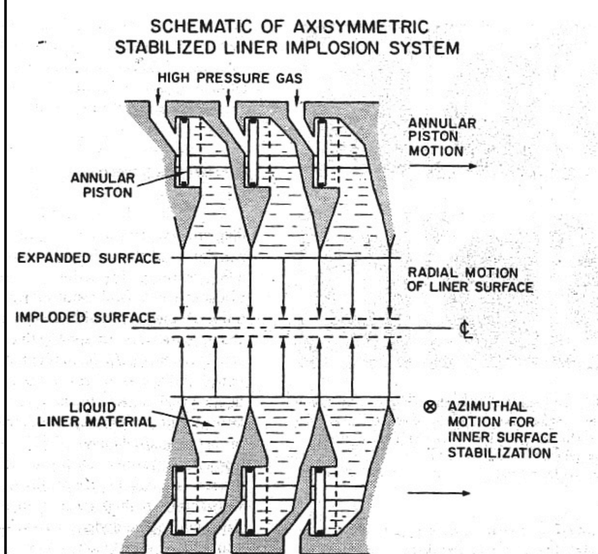
Traveling wave coil compression



Pro: fast, simple, clean

Con: stability of target plasma? Cost of bank?

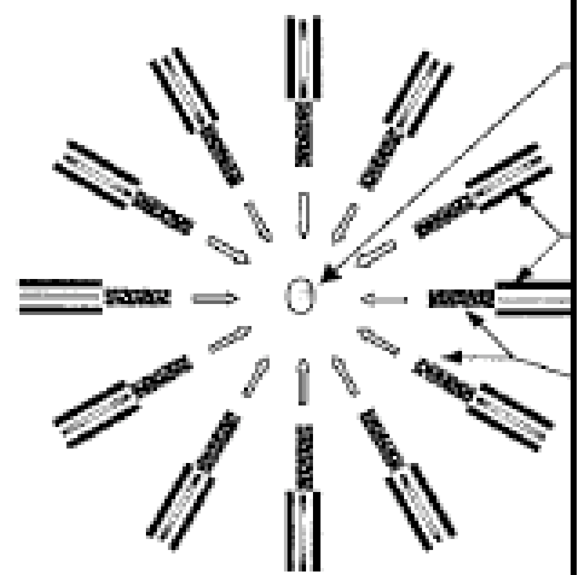
LINUS



Pro: proven

Con: Messy (liquid lead!), slow compression (need target with long life)

PJMTF



Pro: fast, modular, clean.

Con: unproven for compression -

Major design constraint for a Phase II project is cost (350k/year - 2 years, =100k/year machine budget!) ---> collaborative projects best.

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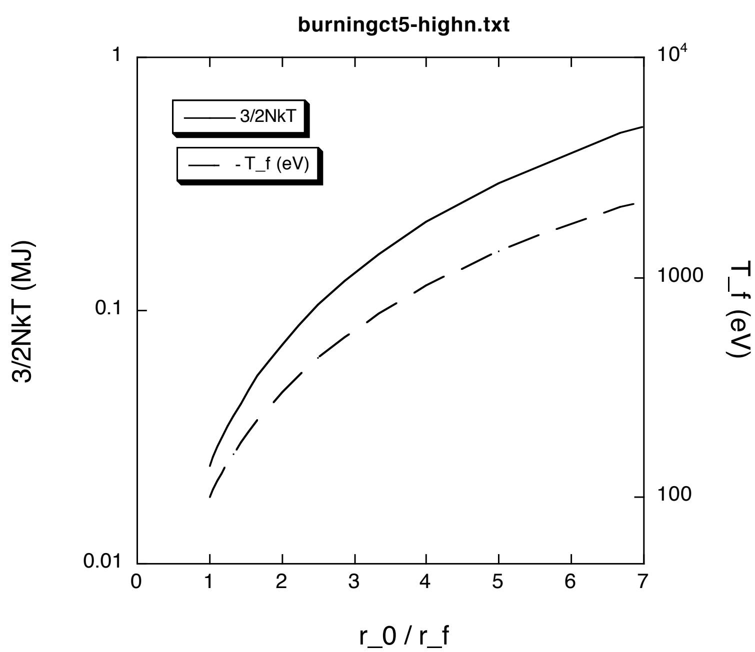
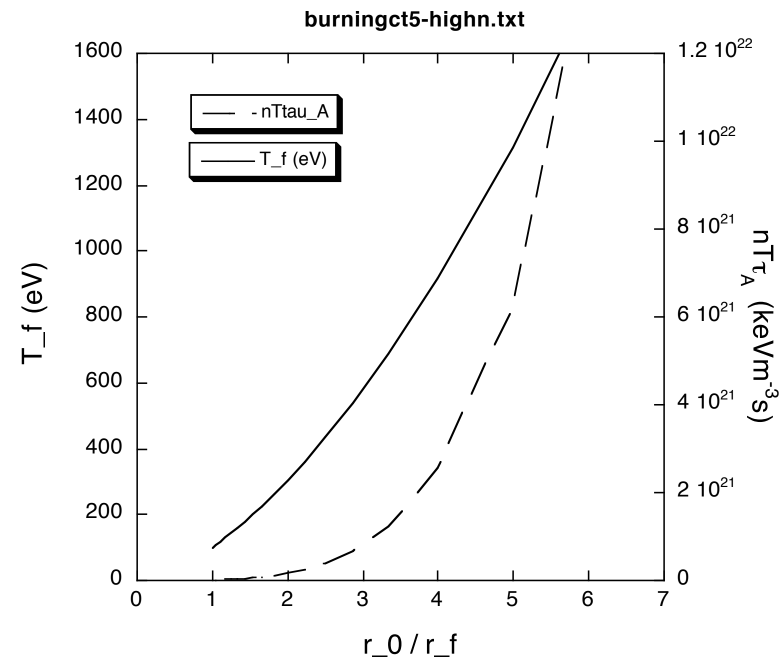
A point design is possible with analytical scaling relations (mostly Spencer).

What are the requirements for reaching the high pressures in a small CT given existing scalings?

Assuming an initial density of n_0=1e24m^{-3}, T_0=100eV, B_0=0.1T, confinement time of ~100μs would need a radial convergence of ~5 to reach fusion-relevance (-->).





<-- Total plasma energy does not get very high: ~300kJ is stored in the plasma, which gives only modest requirements for a compression scheme (assuming good efficiency).

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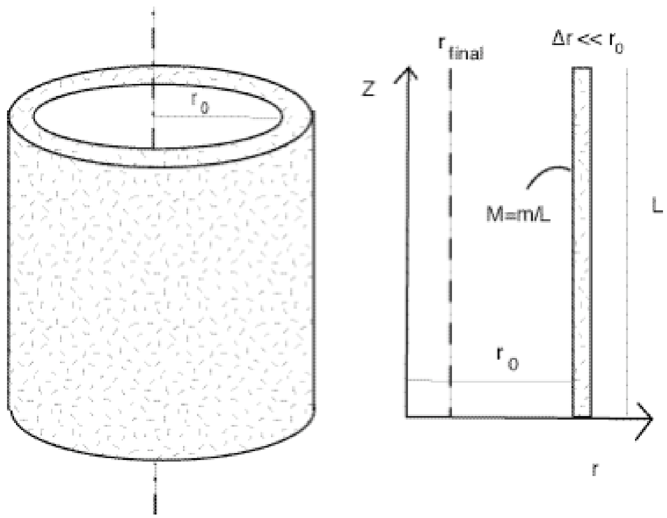
Energy requirements for a liner implosion could be moderate on a small scale.

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Following Ryutov and Drake
---------------------------------------------------------------------
M d^2 r/dt^2  = - 2\pi r p                      (1)
where M is the mass PER UNIT LENGTH of the heavy cylindrical liner.
Multiplying by dr/dt and integrating gives
M (dr/dt)^2/2  = \pi p (r0^2 - r^2)            (2)
Taking r->0 gives the velocity at the final stage of the implosion,
vf  = (2\pi p/M)^1/2  r0                        (3)
Integrating eq (2) gives the "run-in" time:
t_run-in  = sqrt(M/(pi p)) \int_r0^0 dr/sqrt(r0^2-r^2)
             = (\pi/sqrt(2)) r0/vf
             = 2.2 r0/vf                           (4)
---------------------------------------------------------------------
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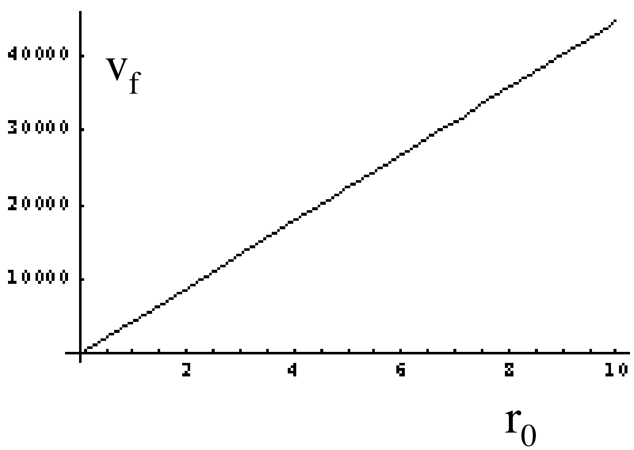
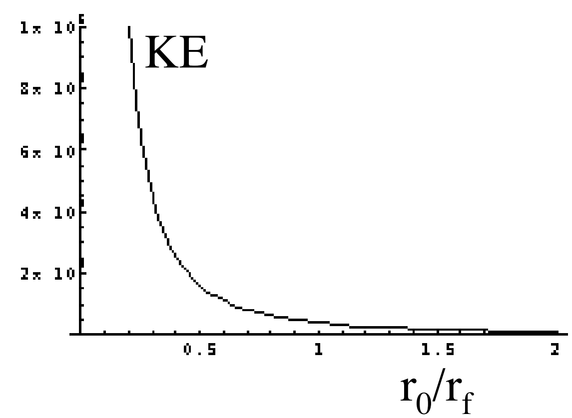


Given constant p, final liner velocity is just a linearly proportion to r_0, giving $v_f \sim 10^4$m/s for p~10^5Pa, L=1m, r0=10m.

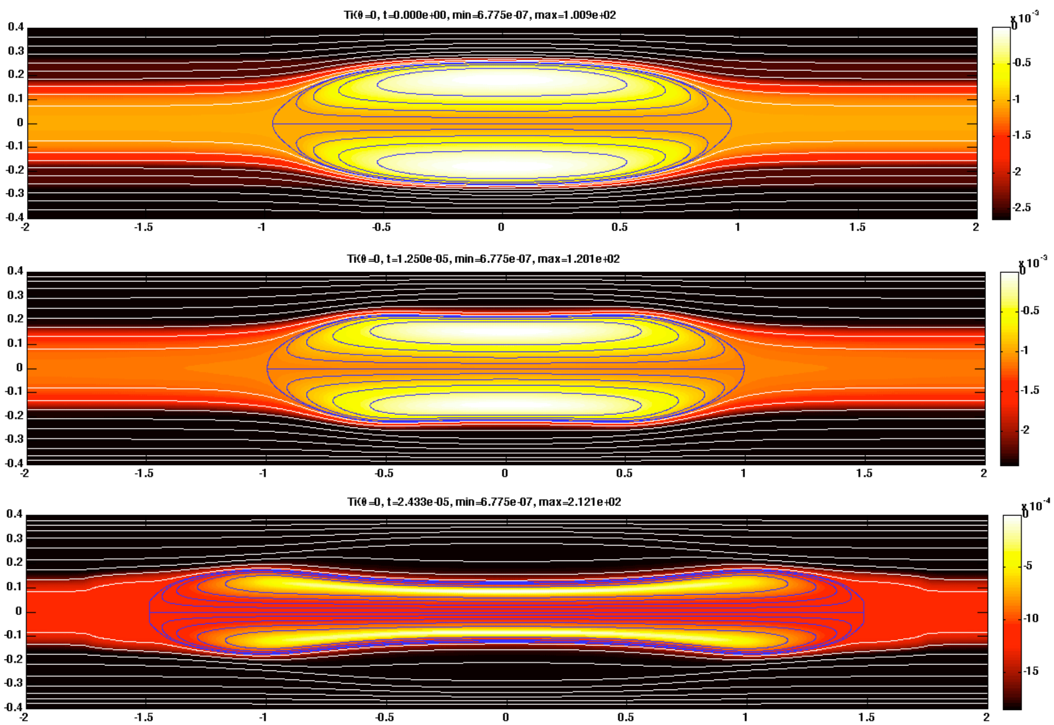
For r_0=2m, liner energy reaches ~10MJ for $r_0/r_f \sim 3$.

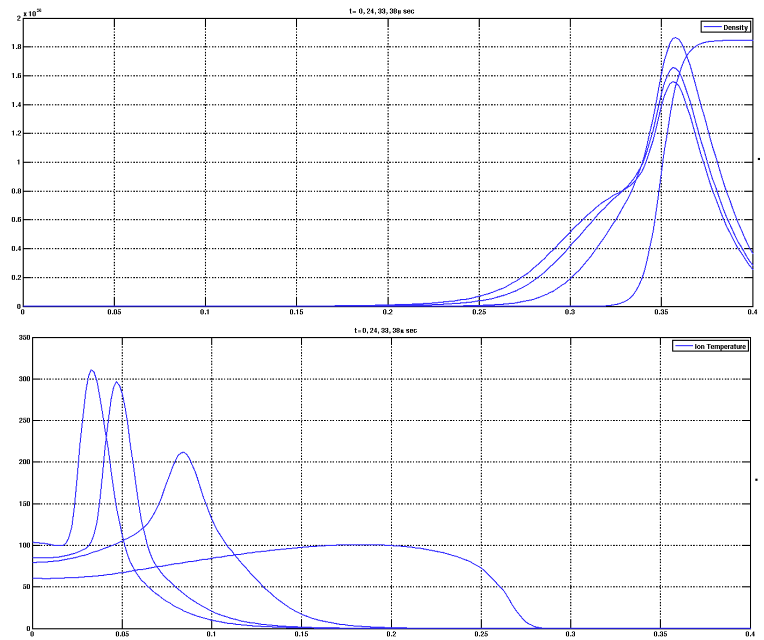


Initial simulation of liner dynamics: compression of a CT target.

Problem set up with NIMROD - aiming to address the dynamics of a liner compression.

Density profile varies by 10 orders of magnitude to simulate liner.





^ shows density as a function of radius and plasma pressure with r, and Ti as function of r.

<-- shows contours of Ti, without any shaping of liner, FRC tends to be pushed out of the ends.

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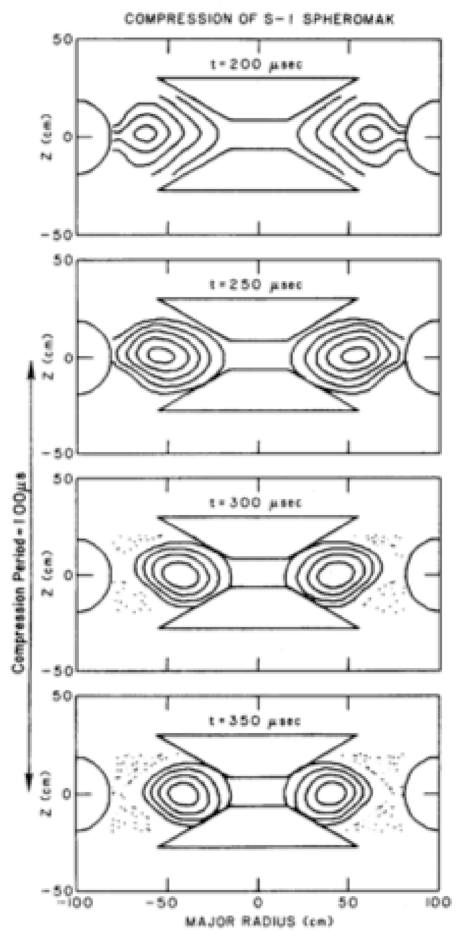
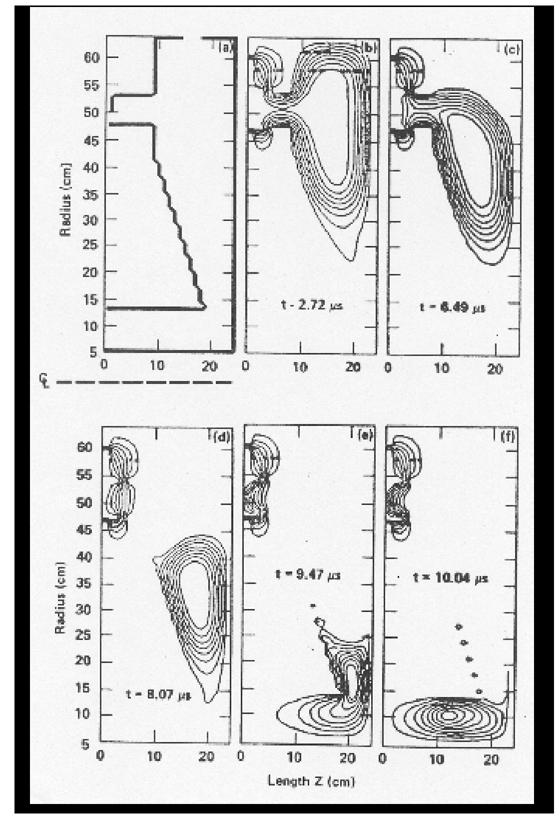
Compression of the final spheromak could proceed like S-1 (cone ensures stability to tilt)

Results from the S-1 spheromak and prior numerical modeling suggest that stability to tilting can be maintained by use of a cone section.

CONCEPT for PHASE II: Compress the plasma radially into a tapered flux conserver, preserving both aspect ratio (hence stability to tilt) and q-profile during compression (object compressed self-similarly).



Yamada



Shumlak

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Concept and issues to be addressed in coming months (before Phase II deadline)

CONCEPT for PHASE II: Compress the plasma radially into a tapered flux conserver, preserving both aspect ratio (hence stability to tilt) and q-profile during compression (object compressed self-similarly).

ISSUES:

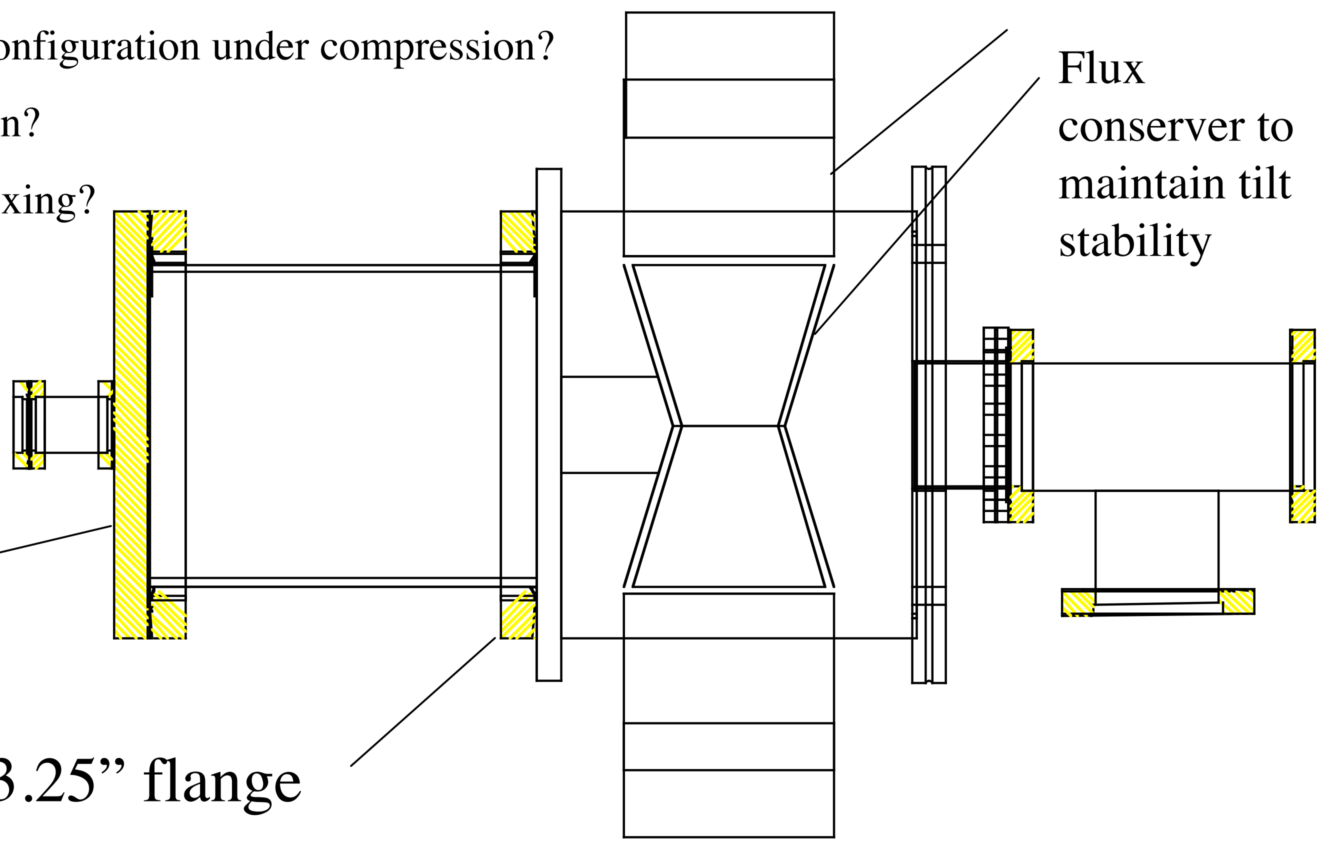
What is the stability of the configuration under compression?

How to drive the compression?

What will be the effect of mixing?

How will the scaling go?

One shot then what?



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Summary

--Progress with experiment and theory for compression of magnetized plasmas.

--We are seeking support for our Phase II project to push it into the commercialization phase.

--We are interested in examining the compression of compact tori in the Phase II of our Phase I project.

WS would be happy to help support other innovative confinement concepts.